Journal of Air Transport Management 124 (2025) 102742

Contents lists available at ScienceDirect

Journal of Air Transport Management

journal homepage: www.elsevier.com/locate/jairtraman

Impact analysis of Russian-Ukrainian war on airspace

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ARTICLE INFO

Keywords:
Airspace
Air transportation
Network
Horizontal flight efficiency
Closed airspace
Civil aviation

ABSTRACT

The operation of global air transportation system is based on the safety and efficiency of provided services. Limiting airspace by closing some volumes requires reconfiguration of airplane trajectories. Russian-Ukrainian war led to the closure of the Ukrainian airspace for any civilian use since February 24, 2022. Airspaces of the Russian Federation and Belarus are limited in use due to sanctions and the high risk of military actions. In addition, ongoing military conflicts in the Middle East region hold airspaces of Afghanistan, Iran, Iraq, Syria, and Yemen at high risk for civil aviation. Airspace users have to avoid entering closed airspace, which results in increased trajectory length, total flight time, aircraft costs, and ticket prices for passengers. In our study, we analyzed the configuration of the closed airspace and its impact on the global air transportation system. A global air transportation graph is used to estimate additional trajectory length and horizontal flight efficiency for a particular departure airport. The impact of closed airspace configuration is estimated based on cumulated functions of the affected area by particular levels of additional trajectory length and horizontal flight efficiency index. Affected areas are estimated for Schiphol (EHAM) and O'Hare (KORD) international airports. Statistical analysis of trajectory data of particular flights indicates a significant increase in additional trajectory length and total flight time. The proposed model has been verified by comparison with the results of trajectory data analysis of 20 unique flight connections.

1. Introduction

Civil aviation is one of the key elements in the global transportation system. Air transportation provides a unique service with a direct connection between many places in the world within the shortest time. Multiple advantages of air transportation stimulate the continuous growth of civil aviation. A clear growth trend can be observed in the number of connections, number of services provided, number of flights, passengers, and cargo transferred. The history of civil aviation development indicates a tendency for growth except for a few periods when degradation caused by global economic factors has appeared. In 2020 global air transportation system faced a huge decrease in traffic caused by the COVID 19 pandemic (Sun et al., 2020; Bao et al., 2021). Global lockdown rolled back the number of flights and passenger traffic for the levels of two previous decades period (Fig. 1). The overall reduction of passenger traffic in 2020 reached 2.7M (Sun et al., 2021; ICAO, 2022). In 2023 European air traffic remained at 8.5% below the pre-pandemic level of 2019 (Eurocontrol, 2023). Results of air traffic prediction expect to reach pre-pandemic level by 2026 at least (Eurocontrol, 2023).

Numerous research connects periods of low growth with different economic factors (Ocheni et al., 2020; Inan and Gokmen, 2021), but it also shows a good correlation with periods of an active phase of military conflicts in the Middle East region (Fig. 1). Beginning of Afghan war in 1978 and Iran-Iraq war in 1980 could be associated with a 5-year period of low trends in air transportation. Persian Gulf War (1990–1991) and the beginning of the Bosnian conflict in Eurocontrol (2023) are correlated by time with the second low trend period. The beginning of Afghan war in 2001 and Iraq war in 2003 coincides with the third period of decline in air transportation (Britannica, 2024). The fourth period was caused by the global financial crisis which affected all sectors of the global economy in 2007. The mentioned wars did not cause a low trend in global passenger traffic. However, they were affected by numerous problems in the global economy that occurred during these periods.

Military actions across countries require closing the airspace for any civilian use to minimize risks in transportation system. The representative authority of each country informs the international aviation community about the risks of airspace use and may restrict access to civil aviation. Restrictions could be applied for some part of the airspace or

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https://doi.org/10.1016/j.jairtraman.2025.102742
Received 2 June 2024; Received in revised form 13 December 2024; Accepted 10 January 2025
Available online 22 January 2025

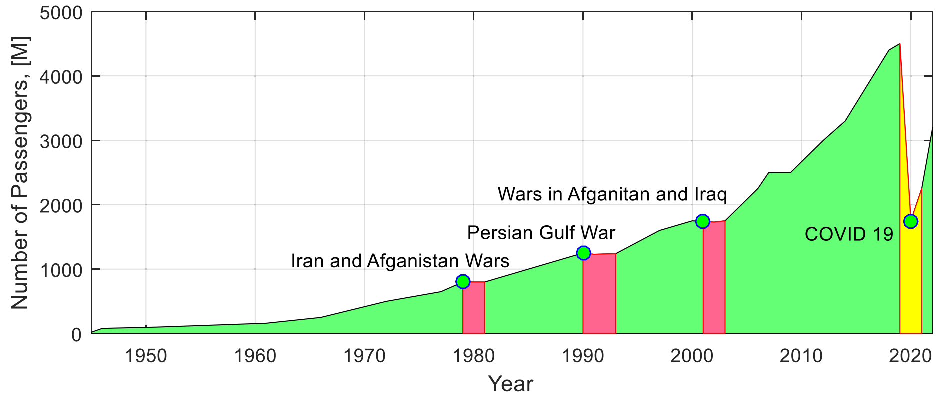

Fig. 1. Global passenger traffic. Source: own authors' representation of data in (ICAO, 2022).

for the whole airspace within the administrative boundaries of the country. Information about closed area geometry with a duration of acting restrictions is published officially. Airspace users use these data to avoid airplanes entering restricted airspace volumes for upcoming flights.

Airplane trajectory is configured based on multicriterial tasks which are grounded on minimal costs, short distance, and flight duration. Effective airplane trajectories planned through restricted airspace have to be replanned with worthy trajectory configurations. The level of impact of restricted airspace on flight efficiency depends on the geometry of closed airspace.

The Russian-Ukrainian War is affecting a large airspace volume that has a dramatic influence on the global air transportation system. The war caused the closure of Ukrainian airspace and limited use of airspaces of the Russian Federation and Belarus. The joint area of involved airspaces is about 18 M km^2 which is the biggest airspace segregation from the period of the "Cold War". However, the most significant one is the configuration of the involved airspace which is placed between 22.1° and −168.9° meridians. Analysis of air traffic shows that most transit flights from North America to Asian destinations have been replanned with a significant increase in flight duration (Akbarlı et al., 2022; Ostroumov et al., 2022). Direct flight connections between North European and Asian countries are affected as well (Chu et al., 2024; Ivannikova et al., 2024). Trajectory replanning caused growth in airfare for end users of air transportation services (Ennen and Wozny, 2024).

In our study, we analyzed the configuration of limited-to-use airspace caused by the Russian-Ukrainian war. Most transit traffic has replanned airplane trajectories to avoid entering closed and limited-in-use airspaces. Parameters of additional trajectory length and horizontal flight efficiency have been used to identify the effect on flights in the global air transportation network. Pairs of flight connections within global airspace have been identified. An area of a particular parameter level is used as an indicator of closed airspace impact on the global transportation network.

The main contribution of the paper is a model for analysis of the impact of closed airspace in flight connections around the globe based on the global air transportation graph. The proposed model could be used to analyze the configuration of any closed airspace in performance of flight connections in the air transportation system. In comparison to present studies the proposed model is useful for analyzing the impact of geometry of closed airspace for any potential flight connections.

An impact of limited airspace caused by the Russian-Ukrainian war has been estimated to support traffic in scenarios: Europe to Asia and North America to Asia. Affected geographical regions by particular levels of additional trajectory length and pairs of the most affected flight connections have been identified.

The paper is structured as follows: in Section 2 a literature review is given. Section 3 describes the methodology used in the research. Section 4 analyses the geometry of limited in use airspace caused by the war in Ukraine. Section 5 presents the results of impact analysis of closed airspaces and statistical analysis of air traffic data.

2. Literature review

Nowadays global air transportation faces new challenges of closing and limiting the use of large airspaces, mostly caused by the war in Ukraine, which started on February 24, 2022 (Akbarlı et al., 2022; Ostroumov et al., 2022). The configuration of the involved airspace (Ukraine, Russian Federation, and Belarus) is big enough to provide a significant impact on global air transportation ecosystem. In addition, the situation has gotten worse due to simultaneously closed airspaces in the Middle East region (Iran, Iraq, Afghanistan, and Syria) (Adler and Hashai, 2005; Safeairspace, 2024) for a long duration. Thus, the air transportation system meets significant limitations from airspace usage.

Analysis of local traffic in Ukraine shows that in the first seven weeks of the war, nearly 10 Million km and 14 thousand hours of flights have been cancelled (Ostroumov et al., 2022). Results of the war's overall impact on the aviation sector point out that significant changes in flight routes caused an increase in total flight time and change in flight costs (Akbarlı et al., 2022; Ivannikova et al., 2024).

Closure of Ukrainian airspace leads to the redistribution of traffic at the airports of neighbouring countries to provide access to air transportation services. Results of the analysis show that in three weeks after the conflict, 107 new airlines were launched in the neighbouring countries to Ukraine. About 734.5 flights per week have been added, which leads to the increase of 25.6% in total flight numbers (Chu et al., 2024).

Airfares of affected flights connections have been increased by 5.4% mean. Also, each additional minute of flight time leads to an average fare increase of around 1.56 USD (Ennen and Wozny, 2024).

The safety of air transportation is also significantly affected by the war in Ukraine because of military actions and the wide intentional jamming of navigation systems of airplanes. Numerous studies show that long periods of Global Navigation Satellite System signal jamming in the Eastern Europe affect civil aviation (Felux et al., 2023; Wu, 2024).

The majority of studies on the impact of the war in Ukraine on global air transportation based on trajectory data processing were obtained under Automatic Dependent Surveillance-Broadcast (ADS-B) technology (Chu et al., 2024; Ostroumov et al., 2022). Results of trajectory analysis of performed flights for connections between Asia-Europe and Asia-North America show huge impacts of closed airspace on global air transportation system based on increased trajectory length and total flight time (Chu et al., 2024; Ivashchuk and Ostroumov, 2023). It is also proved by statistical analysis of air traffic using airlines' databases of actual flights (Ivannikova et al., 2024). Unfortunately, the analysis of already performed flights is based on statistical data which highly depends on the logic of trajectory planning tools used in airlines (Lindner et al., 2020). Actual weather has significant influence on choosing an

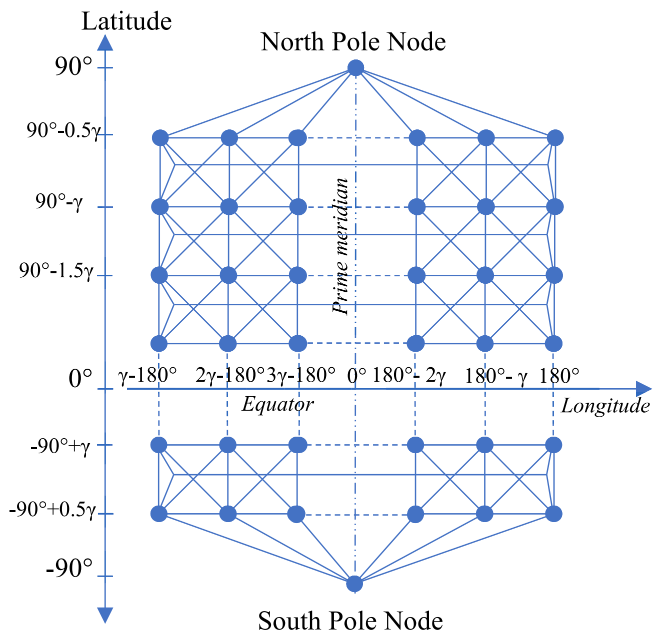

Fig. 2. The geometry of global transportation graph. Source: own elaboration of authors.

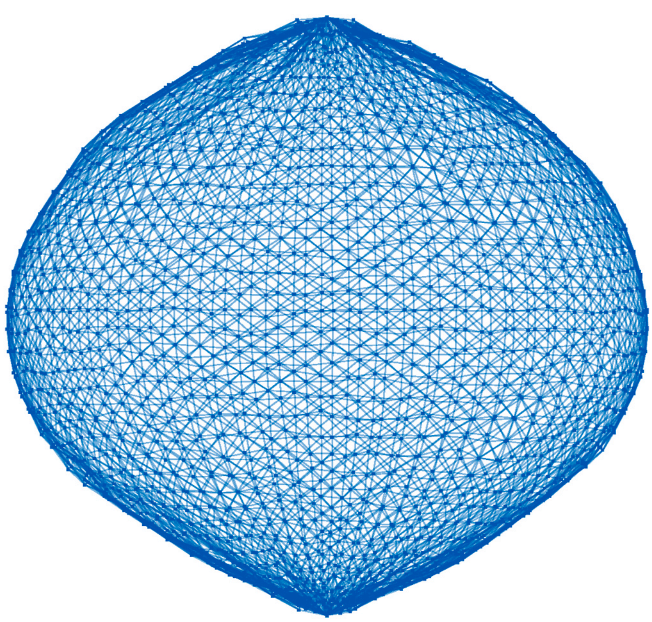

Fig. 3. Global transportation graph. Source: own figure generated in the developed software.

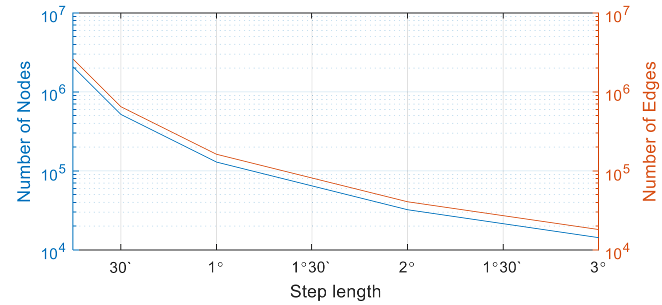

Fig. 4. Parameters of global transportation graph connected with the step length. Source: own figure generated in the developed software.

optimal flight path in most planning tools. Airplane trajectories are selected in this case on the bases of wind parameters distribution to make the most cost-efficient flight plan. The configuration of the closed airspace is large enough to participate in the formation of different weather regions on the Earth. Therefore, planned trajectories may significantly differ because of the seasons.

The primary limitation of impact analysis based on ADS-B trajectory data processing lies in its reliance on historical flight connection data. This approach restricts the analysis to connections that are already present in the existing data pool, making it impossible to assess the impact of flight connections that have not been previously realised.

Another approach to measuring the impact of closed airspace on global air transportation system could be based on flight-routes network analysis (Zanin and Wandelt, 2023; Azzam et al., 2013). Flight routes of closed airspace could be excluded from the global air transportation network. Currently, the global airspace structure is in fundamental changes due to Free Route Airspaces (FRA) that are implementing worldwide (Nava–Gaxiola et al., 2018; Tominaga et al., 2023; Hirabayashi et al., 2021). FRA shuts down the conventional flight routes network and makes airspace users free in the selection of their trajectories. FRA makes it possible to use the most cost-efficient trajectories for airspace users and increase airspace capacity significantly, which stimulates further growth of air traffic. Airplanes could use direct, linear flight from the point of entering the airspace to the point of leaving FRA. Also, users could specify user-based waypoints to make a manoeuvre within FRA. Implementation of FRA in the European airspace was started in 2011 and is going to be completed by 2025 (Sesar, 2019; EU, 2011).

Civil aviation directly depends on the airspace configuration in which it operates. Meteorological conditions or hazardous weather phenomena can limit airspace usage significantly. Military conflicts are another important reason to close airspace for a long time. Airspaces of areas with active phases of military conflict caused a high level of risk for civil aviation due to military action or anti-aircraft missile usage. Civil airplanes could be classified incorrectly or could be an error for automatic air defence systems. Unfortunately, there have been too many catastrophes of civil airplanes caused by military action in the last decade. Flight PS 752 of Ukraine International Airlines (B 737) was misidentified as a hostile target by the air defence system and shot down by Iranian armed forces on Jan 8, 2020, during the movement by the standard instrumental departure scheme (AAIB, 2021). Flight MH17 of Malaysia Airlines (B 777) was shot down by a surface-to-air missile in Ukrainian airspace on Jul 17, 2014 (JIT, 2023). Flight of military Unmanned Aerial Vehicles in fully automatic mode is another serious hazard for civil aviation in areas of military conflicts. Jamming and spoofing of navigation signals is another type of threat in which civil airplanes could be influenced not only in areas of military conflict but also in neighbour's airspaces (Wu, 2024). All of these facts indicate the necessity to limit access of civil air traffic to airspaces with a high risk of military action. Military conflicts mostly coincide with administrative boundaries of particular airspace. Therefore, closing the airspace of the country is a required step to ensure the safety of air transportation.

3. Methodology

The impact of closed airspace on the global air transportation system can be assessed by calculating the additional trajectory length required to bypass restricted airspace. A global air transportation graph is used to simulate airplane movements within FRA. The nodes of graph specify possible airplane positions and edges indicate a path of airplane movement. Each node is associated with a point of a particular geographic location. The coordinates of nodes are selected based on a specific grid step. We use different grid steps for latitude and longitude to have the same number of nodes in the West-East and the North-South sides. The

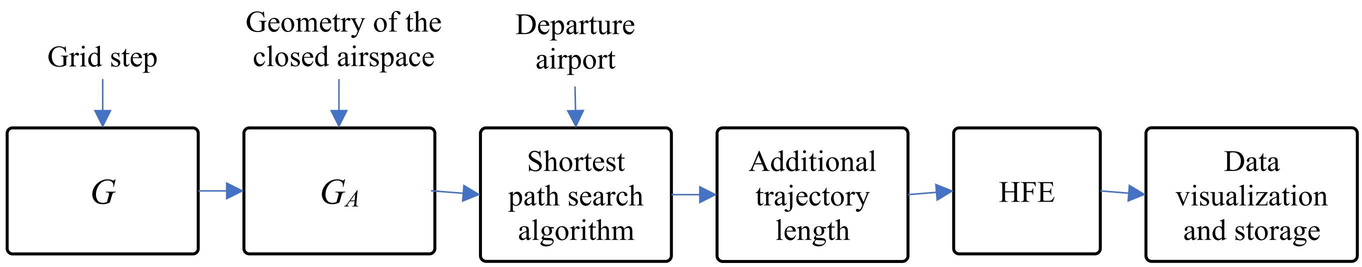

Fig. 5. Structural scheme of the simulation software. Source: own elaboration of authors.

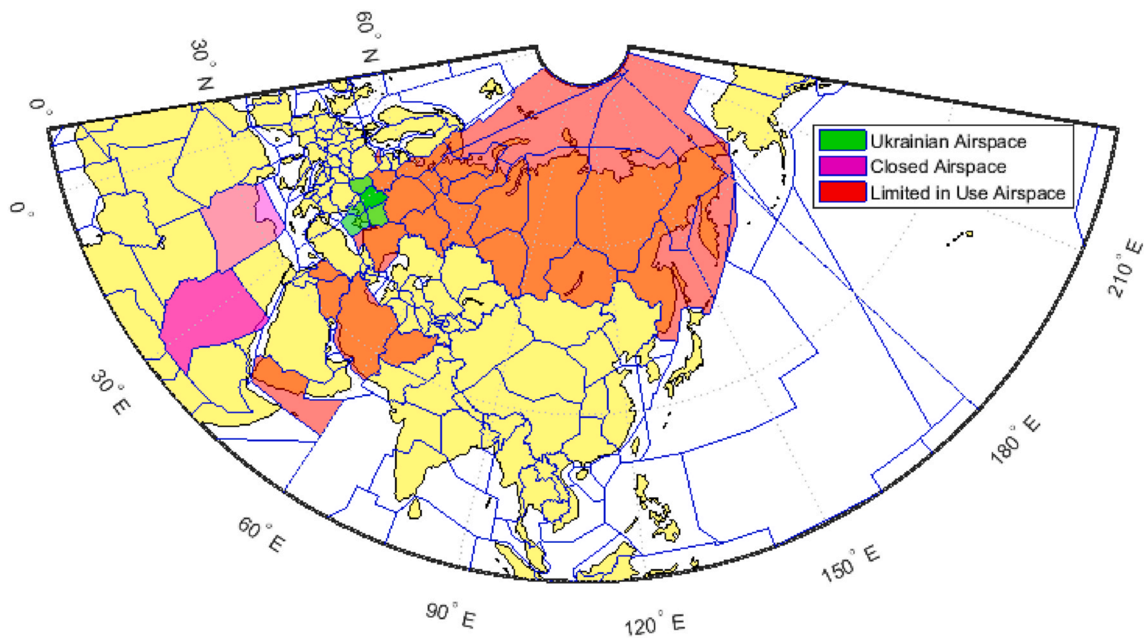

Fig. 6. Configuration of the closed and risky airspace (May 2024). Source: own figure generated in the developed software.

Table 1
Configuration of the closed airspace.

Country	Airspace geometry	Area, [km^2]	FIRs	Status
Ukraine	22.14E to 40.20E 42.87N–51.92N	773.9×10^3	UKLV, UKBV, UKDV, UKOV, UKFV	Closed
Russian Federation	19.6273E to −168.9897W 41.1961N to 90 N	24.96×10^6	UMKK, ULLL, ULWW, ULKK, UWWW, USSV, ULMM, ULAA, UUYY, USTV, UNNT, UNKL, UIII, UHHH, UEEE, UHPP, UHMM, UUWV, URRV	Limited in use
Belarus	23.1666E to 32.771E 51.2622N–56.1666N	208.0×10^3	UMMV	Limited in use
Afghanistan	60.4835E to 74.8775E 29.3833N–38.4834N	641×10^3	OAKX	Limited in use
Iran	44.0473E to 63.3332E 24.66N to 39.7762 N	1.79×10^6	OIIX	Limited in use
Iraq	38.7935E to 48.75E 29.0611N to 37.3809 N	436×10^3	ORBB	Limited in use
Syria	35.4833E 42.3834E 32.33094N 37.3192N	190×10^3	OSTT	Limited in use
Yemen	42.5558E to 54.4769E 11.75N–19.79N	1.19×10^6	OYSC	Limited in use
Libya	9.3832E to 25.1329E 19.5N–34.3333N	2.03×10^6	HLLL	Closed
Sudan	21.8335E to 38.50E 3.997N–22.0N	2.5×10^6	HSSS	Closed

Source: own elaboration.

grid step in latitude (0.5γ) is half of the grid step in longitude (γ). Different grid steps could be used to get the required precision level in analysis. As an example, a grid step in 30 min divide the latitude side (from −180W to +180E) into 719 equally distributed nodes and 360 nodes placed at each meridian. Two nodes are placed in the True North and South poles. In total 258842 nodes are used in grid step 30 min.

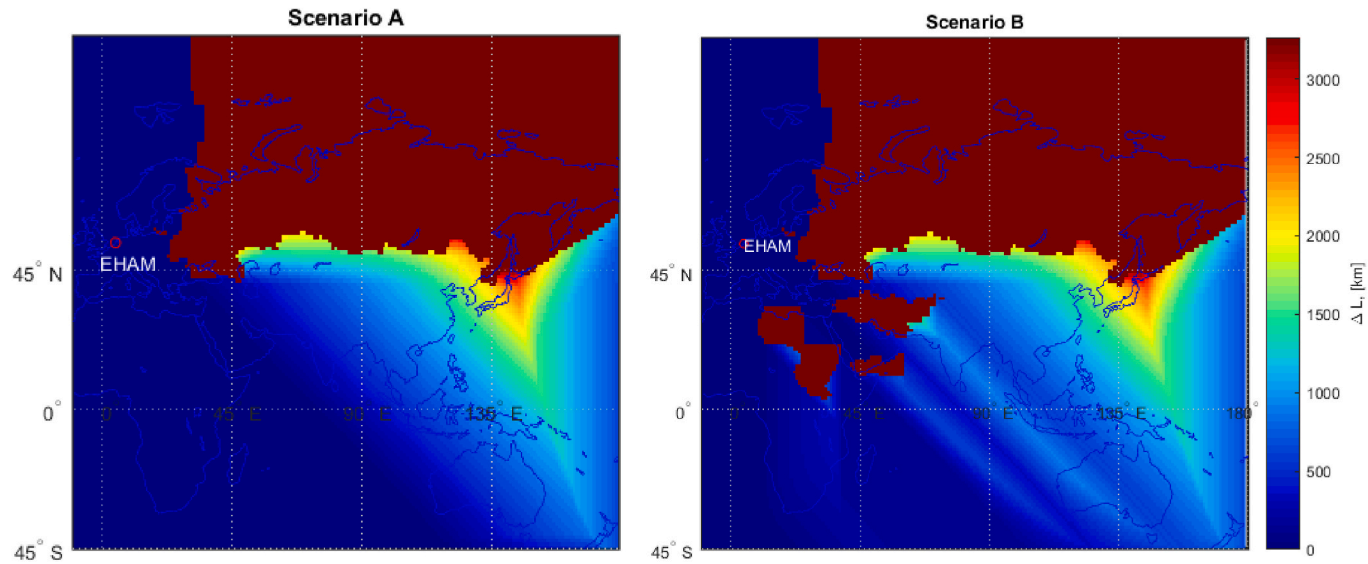

Fig. 7. Additional length in flight connections from Schiphol Airport. Source: own figure generated in the developed software.

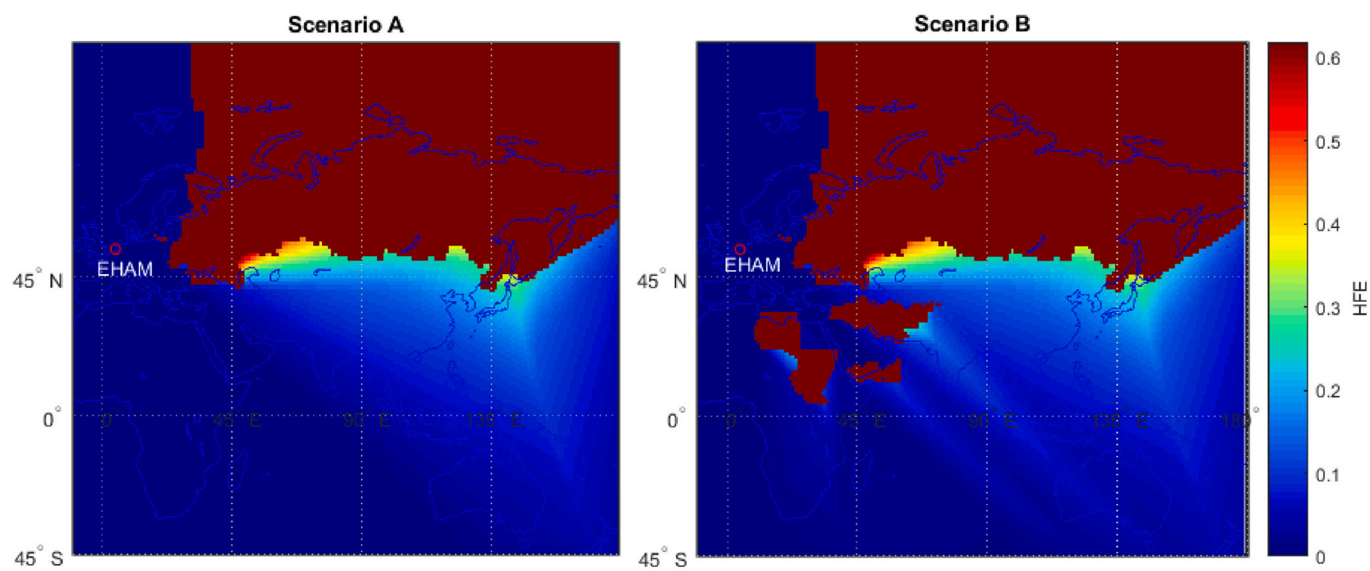

Fig. 8. HFE for flight connections from Schiphol Airport. Source: own figure generated in the developed software.

Nodes are connected with edges that coincide with parallels and meridians. Also, we use diagonal edges for each group of neighbour nodes. The geometry of the global transportation graph is represented on Fig. 2.

Each node placed at the top parallel is connected with the North Pole node and each node of the bottom parallel is connected with the South Pole node. Configuration of the global transportation graph for $\gamma = 5^\circ$ is presented on Fig. 3.

The weight of each edge could be calculated as an arch length of a great circle between nodes which gives the shortest path on the spherical surface as follows (Chopde and Nichat, 2013):

$$w = 2R \arcsin\sqrt{\cos(\varphi_1)\cos(\varphi_2)\sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right) + \sin^2\left(\frac{\varphi_2 - \varphi_1}{2}\right)} \quad (1)$$

where R is the radius of the great circle; λ and φ are the longitude and geocentrical latitude of the start and end points.

The grid step identifies the precision of trajectory analysis. On the other hand, the number of nodes and edges depends on the grid step (Fig. 4).

Global transportation graph (Fig. 3) utilized the possibility of airspace users to plan a flight route in such a way to connect any places in the world with a particular level of precision. The optimal trajectory could be selected by one of the shortest path selection algorithms. Different algorithms could be used to solve the shortest path problem. Recent scientific research indicates a wide variety of methods for determining the shortest path, including genetic algorithms, Gray Wolf Optimization algorithms, ant colony methods, and other machine learning methods (AbuSalim et al., 2020; Dhulkefl et al., 2020).

Dijkstra's algorithm is a classical tool to identify the optimal path in a graph. The initial information for the implementation of the algorithm is the graph, which contains the nodes (or starting points, stop points on the way to the final point of the route and the final point) and edges on which the cost of reaching the specified nodes is marked. Dijkstra's algorithm is an iterative one. The algorithm sequentially passes through each node and determines the minimum trajectory length to reach its neighbouring nodes. After the analysis of all the nodes, the shortest path is determined by going back through the algorithm from the final point to the starting point.

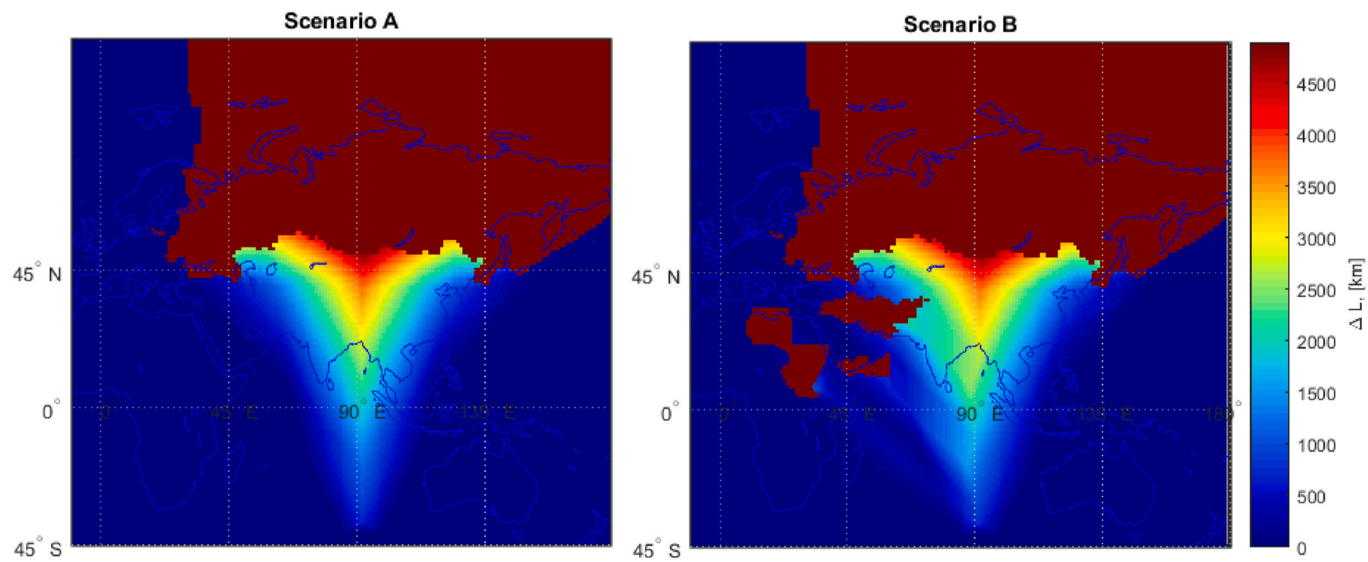

Fig. 9. Additional length in flight connections from O'Hare Airport. Source: own figure generated in the developed software.

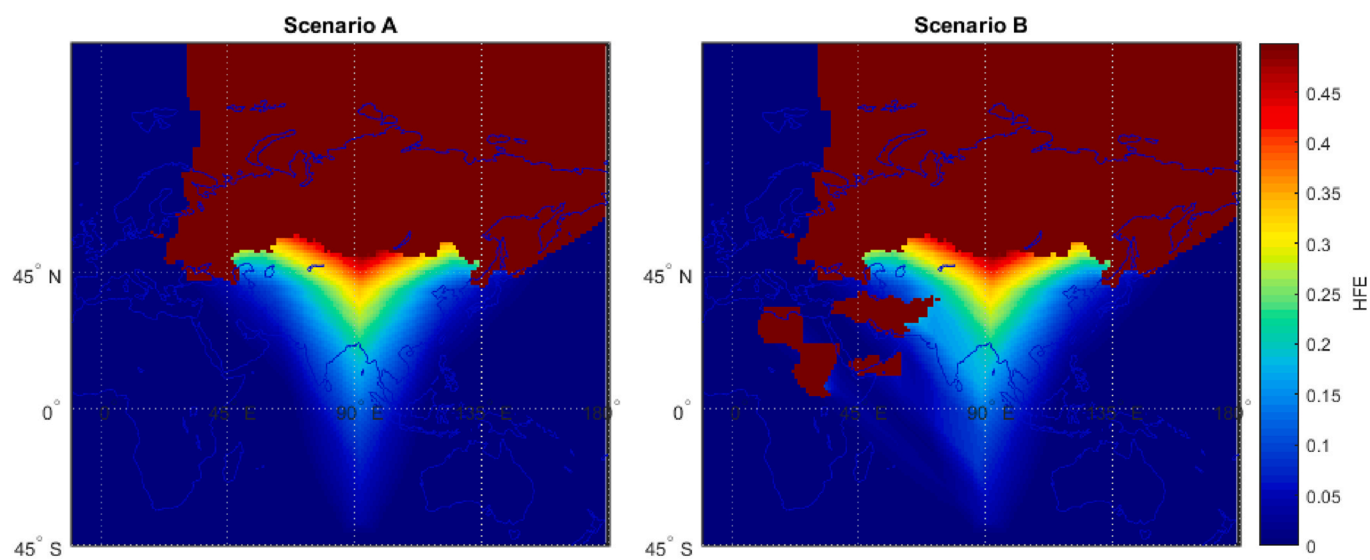

Fig. 10. HFE for flight connections from O'Hare Airport. Source: own figure generated in the developed software.

Dijkstra's algorithm has a number of modifications and improvements that increase its efficiency in terms of speed and ease of data processing (Dhouib, 2023). In particular, Dijkstra's algorithm can be used in conjunction with clustering methods. Such harmonization allows to implement an approach for reinforcement learning of modern artificial intelligence systems. For example, the grid-based DBSCAN image clustering method allows the transformation of the original arbitrary map image into the equivalent of a graph with permitted and forbidden zones, which can be subjected to forward and reverse iterations according to Dijkstra's algorithm. Such and similar optimizations make it possible to turn Dijkstra's algorithm into an intelligent agent, the maximum reward for which will be in the case of finding the optimal route between the starting and final points.

An impact of closed airspace on the formation of the efficient trajectory could be estimated as an increase in total trajectory length. Global transportation graph G is used to get the shortest path as a set of nodes N:

$$G = \{N_1, N_2, N_3, \dots, N_k\}$$

where k is the number of nodes.

Two nodes are connected only by one edge. Therefore, the sequence of nodes in the shortest path identifies the sequence of edges. The length of each edge is calculated by (1) and the total trajectory length is estimated as the sum of edge lengths that create the shortest path:

$$L = \sum_{i=1}^{k} w_i \tag{2}$$

Increasing the number of nodes (reducing the grid step) makes the total trajectory length close to the shortest path length estimated between departure and destination airports.

Nodes placed geographically within the closed airspace should be removed from the global transportation graph and form a limited graph G_A. The difference in short path lengths for G and G_A graphs indicates losses caused by the closed airspace.

The horizontal Flight Efficiency (HFE) of the shortest path in the limited graph is used as an indicator of the impact caused by the closure of airspace. HFE could be estimated as a percentage of additional trajectory length to the shortest path length between departure and desti-

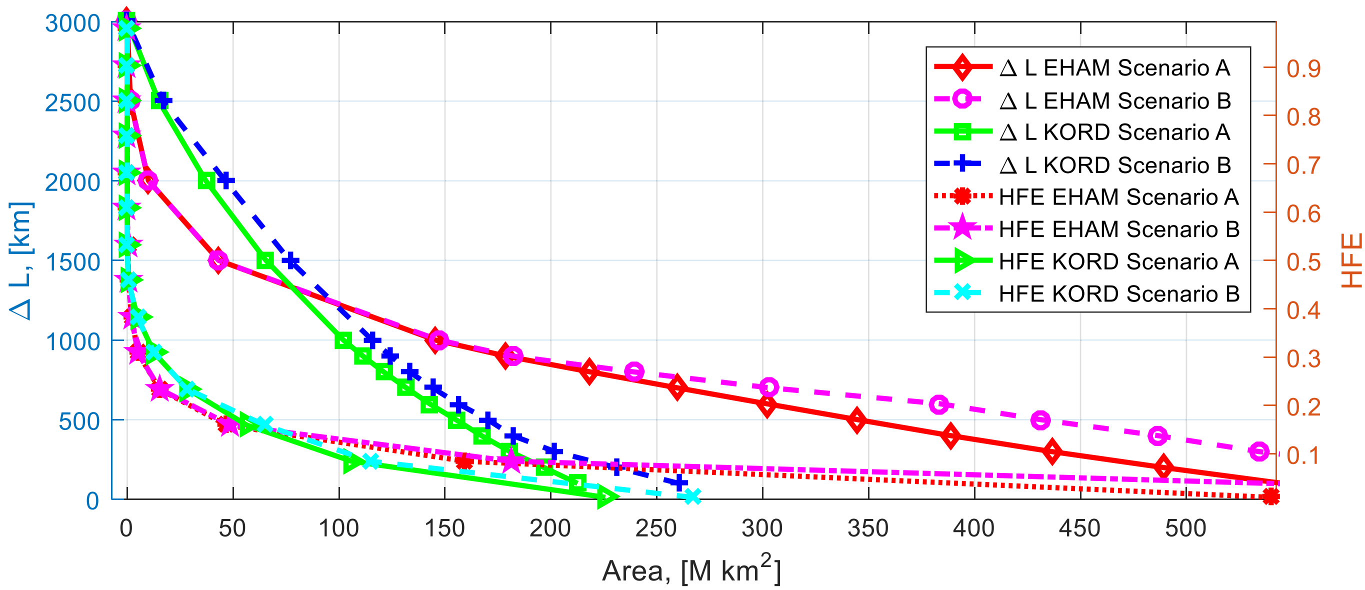

Fig. 11. Affected areas by particular levels of additional trajectory length and HFE. Source: own figure generated in the developed software.

Table 2
Results of statistical analysis of the additional trajectory length for EHAM departure airport.

Destination Country	Additional Trajectory Length			Number of international airports in the destination country
	Mean, [km]	Min, [km]	Max, [km]	
Japan	1694	1327	1956	12
South Korea	1600	1511	1684	5
Mongolia	1596	1596	1596	1
China	1168	797	2002	36
Kazakhstan	1047	734	1571	3
Vietnam	728	658	797	2
Indonesia	722	612	967	5
India	652	492	814	9
Thailand	631	612	658	4

Source: Own calculations results.

Table 3
Results of statistical analysis of the additional trajectory length for KORD departure airport.

Destination Country	Additional Trajectory Length			Number of international airports in the destination country
	Mean, [km]	Min, [km]	Max, [km]	
Mongolia	3011	3011	3011	1
Kazakhstan	2752	2089	3425	3
India	1768	1342	2559	9
Thailand	1493	1396	1761	4
China	1136	338	3676	36
Viet Nam	1049	834	1263	2
Korea	417	309	498	5
Japan	130	76	261	12
Indonesia	126	0	500	5

Source: Own calculations results.

nation airports:

$$HFE = \frac{L - L_{GC}}{L_{GC}} \quad (3)$$

where L is the total short path length in the limited graph estimated by (2); L_{GC} is the shortest trajectory length (great circle trajectory) between departure and destination airports.

HFE indicates an impact of inefficient trajectory per every 1 km of efficient trajectory. Smaller values of HFE correspond to the higher trajectory efficiency. Bigger values of HFE identify the level of trajectory inefficiency.

A specific software has been developed in Matlab to analyze the impact of the closed airspace. The structure scheme of the software is shown in Fig. 5. At the initial stage, based on the input grid step, a global air transportation graph (G) is generated. A graph is set with nodes, the coordinates of which are generated based on the grid step. Edges weight is calculated by (1). The geometry of the closed airspace is specified as a set of geographic points. In our study, we use the global flight information regions database, which provides the shape of selected airspace in TopoJSON data format. A specific parser of TopoJSON data format is used to get the coordinates of the airspace shape in WGS84. A limited graph G_A is obtained from G, by removing nodes that are inside the closed airspace shape.

Departure airport is used to specify the start point of a travel for each other nodes in the G_A graph. Coordinates of the departure airport are selected from the database of global airports by inputting ICAO identification code of the airport. The shortest path is searching for both graphs G and G_A. Additional trajectory length is calculated as the difference between the identified shortest paths for G and G_A. Also, HFE is calculated by (3) for the identified short path. Additional trajectory length and HFE are estimated for each node of G_A. On the bases of the input data, geographic projection parameters of the additional trajectory length and HFE are visualized with the help of a specified colormap. Also, areas, affected by particular levels of additional trajectory length and HFE are estimated as cumulated functions.

4. Geometry of the limited in use airspace caused by the war in Ukraine

The state aviation administration of Ukraine closed Ukrainian airspace at 00:45 UTC on February 24, 2022, due to the high risk of military actions. At the same time, air navigation provider in Ukraine stopped any air navigation services provided to support civil aviation in the following flight information regions (FIR): UKLV (Lviv), UKBV (Kyiv), UKDV (Dnipro), UKOV (Odesa), UKFV (Simferopol) (UkSATSE, 2022; AIP Ukraine, 2024).

Russian Federation closed parts of FIRs of Moscow (UUWV) and Rostov (URRV) in 200NM around the Ukrainian administrative boundary for any civilian use too. Sanctions imposed by the international

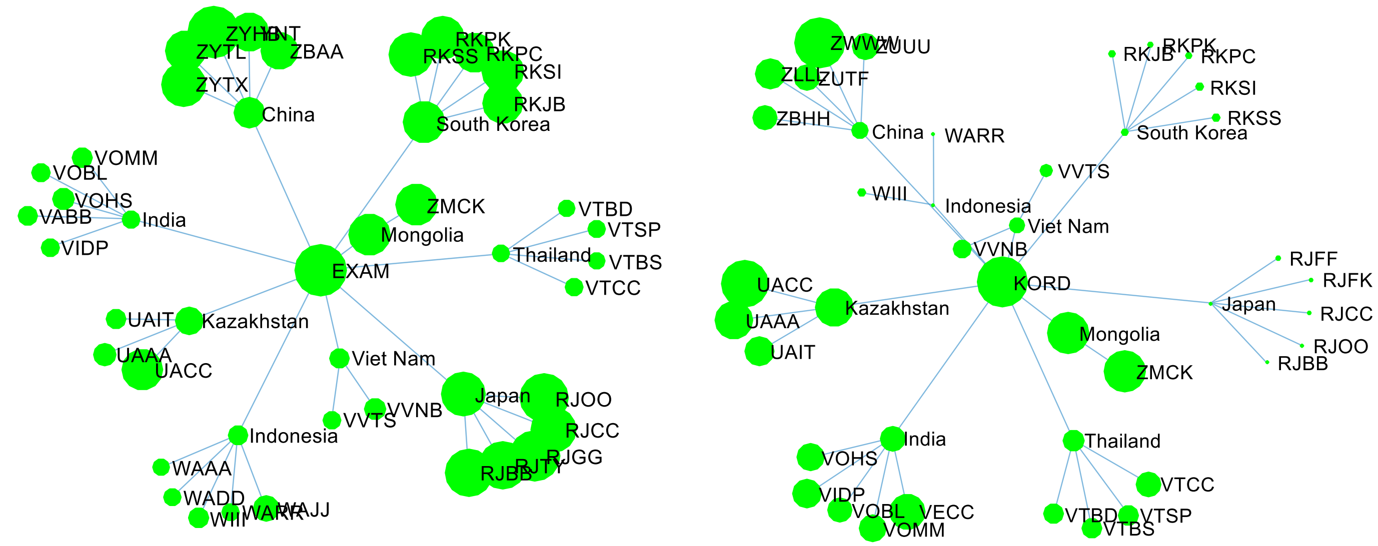

Fig. 12. Graphs of the most affected flight connections grouped by destination countries for EXAM and KORD airports. Source: own figure generated in the developed software.

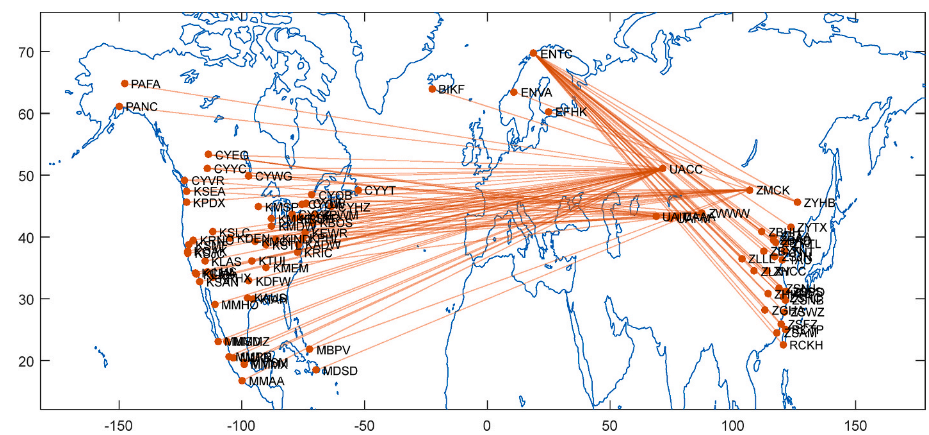

Fig. 13. Top 100 the most affected flight connections due to the closure of the airspace. Source: own figure generated in the developed software.

community to the Russian Federation and the high risk of military action limit the usage of Russian airspace. The following FIRs of the Russian Federation are limited in use: UMKK, ULLL, ULWW, ULKK, UWWW, USSV, ULMM, ULAA, UUYY, USTV, UNNT, UNKL, UIII, UHHH, UEEE, UHPP, UHMM (AIP Russia, 2024).

The airspace of Belarus has been under the sanction of the global aviation community since May 23, 2021, when Belarusian military forces landed a civil passenger airplane (Athens-Vilnius) operated by Ryanair.

Ongoing military conflicts in the Middle East region (western Asia) hold the airspaces of Afghanistan, Iran, Iraq, Syria, and Yemen at high risk. Many aviation authorities recommend to avoid entering these airspace volumes. Airspaces of Libya and Sudan are closed due to ongoing war and military actions in 2023–2024. A dramatic scenario happened in August 2023 when Niger and Mali limited the use of their airspaces for civil aviation due to the military conflict. Airspaces of Niger and Mali together with already closed airspaces of Libya and Sudan limit air transportation for the whole African continent. Configuration of the closed airspace and places with a high risk of military action in May 2024 is presented in Fig. 6 in equal-area conic geographic projection.

Parameters of the airspace configuration involved are calculated based on the FIR shape model and are presented in Table 1.

The configuration of the closed and risky airspaces (Fig. 6) creates perils for direct flight connection with Asian destinations. Limited in use airspace of the Russian Federation, on the North side, affects polar flights for connection with North America. On the West side airspaces of Syria, Iraq, Iran, and Afghanistan limit air traffic flows from Asia. The configuration of the involved airspaces gives a beneficial position to the Turkish airspace, making it useful for direct flights from Asia.

5. Results

5.1. Impact of the closed airspaces

The impact of the geometry of closed airspace on the global air transportation system has been estimated with the help of the developed software (Fig. 5), run in the Matlab computation environment. The study is focused on estimating the impact of the closed airspace caused by the war in Ukraine on flight connections in Europe – Asia and North America – Asia regions.

The impact of the closed airspace configuration is analyzed in two scenarios:

- Scenario A. Consider only airspaces of Ukraine, Belarus, and Russia as closed ones;
- Scenario B. Consider all closed and risky airspaces for May 2024. It includes airspaces of Ukraine, Belarus, Russia, Afghanistan, Iran, Iraq, Syria, Yemen, Libya, and Sudan (Fig. 6).

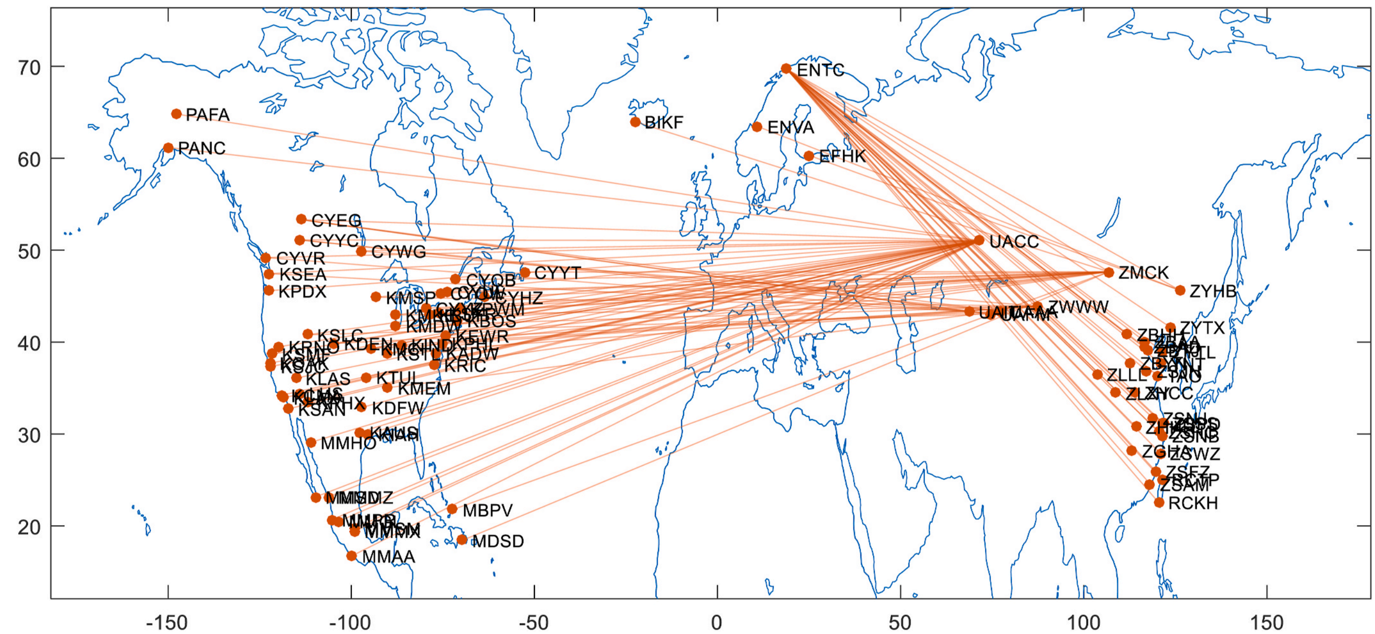

Fig. 14. Trajectories of the flight FIN73 from March 30 to Jun 27, 2024. Source: own figure generated in the developed software.

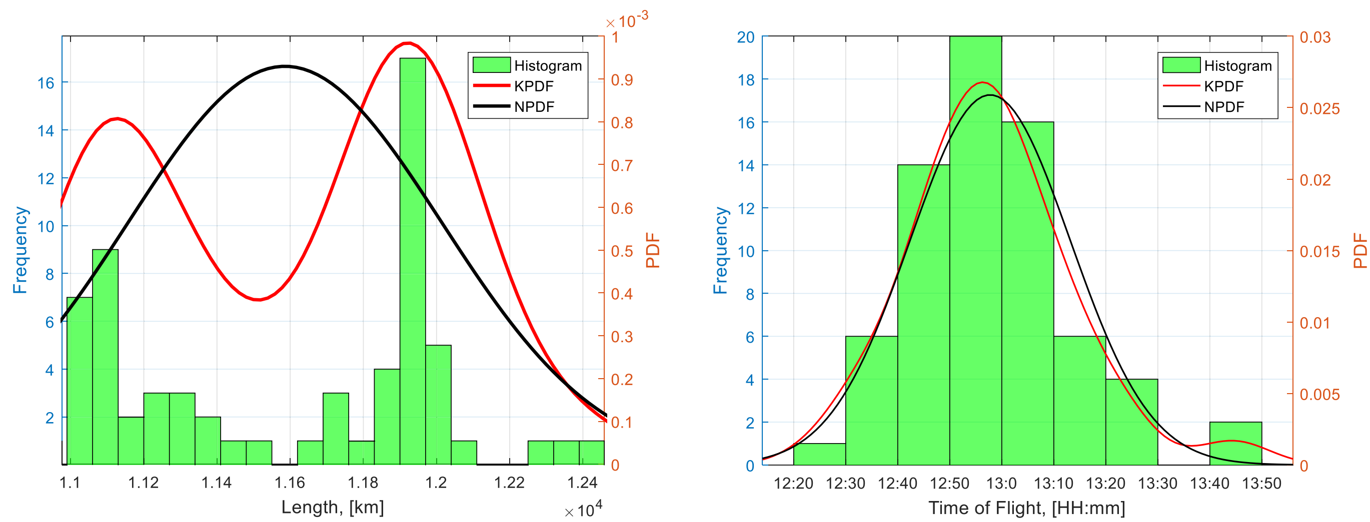

Fig. 15. Results of the statistical data analysis for the flight FIN73 during March–May 2024. Source: own figure generated in the developed software.

The potential of the transportation network to support traffic from Europe to Asia is verified with the help of Amsterdam Schiphol Airport (EHAM, coordinates N52°18.48′, E4°45.85′) which is classified as the second busiest airport in Europe with above 1400 flights per a day (Eurocontrol, 2024). Results of the simulation of both scenarios for flight connections from Schiphol Airport to all other nodes in the network are presented in Fig. 7 for additional trajectory length (ΔL) and in Fig. 8 for HFE (estimated by (3)).

Chicago O'Hare International Airport (KORD, coordinates N41°58.62′, W87°54.49′) is used to verify the impact on North America to Asia flight connections. Obtained results are shown in Fig. 9 for length of addition trajectory and in Fig. 10 for HFE correspondently.

Obtained results for O'Hare Airport indicate a dramatic influence of the closed airspaces on optimal trajectory planning. Direct flights to India and Central Asia have to use highly non-optimal trajectories to avoid entering risky airspace. For example, flight connection from O'Hare International Airport (KORD, US) to Chinggis Khaan International Airport (ZMCK, Mongolia) has 3011 km of additional trajectory length and 0.35 of HFE. This situation caused American Airlines to replace non-stop flights with connecting flights through Europe or Japan.

Flight connection from EHAM airport to Asahikawa Airport (RJEC, Japan) shows an extra 1956 km and 0.33 of HFE.

The total impact of the closed airspace configuration on the whole network could be estimated based on the impact area. An area of a particular level of additional trajectory length is used to find a cumulative distribution function. The results of the impact area analysis are shown in Fig. 11.

The obtained results in Fig. 11 show that for the KORD departure airport (scenario A), an additional trajectory length of at least 1000 km has been identified in area of 100 M km^2. However, for the EHAM departure airport (approximately the same result for both scenarios A and B) additional trajectory length of 1000 km is obtained in area of 147 M km^2. Analysis of cumulation functions indicates that area of the involved airspace (for a wide range of ΔL) is much bigger for EHAM than for KORD. However, in areas less than 100 M km^2 values of ΔL are bigger

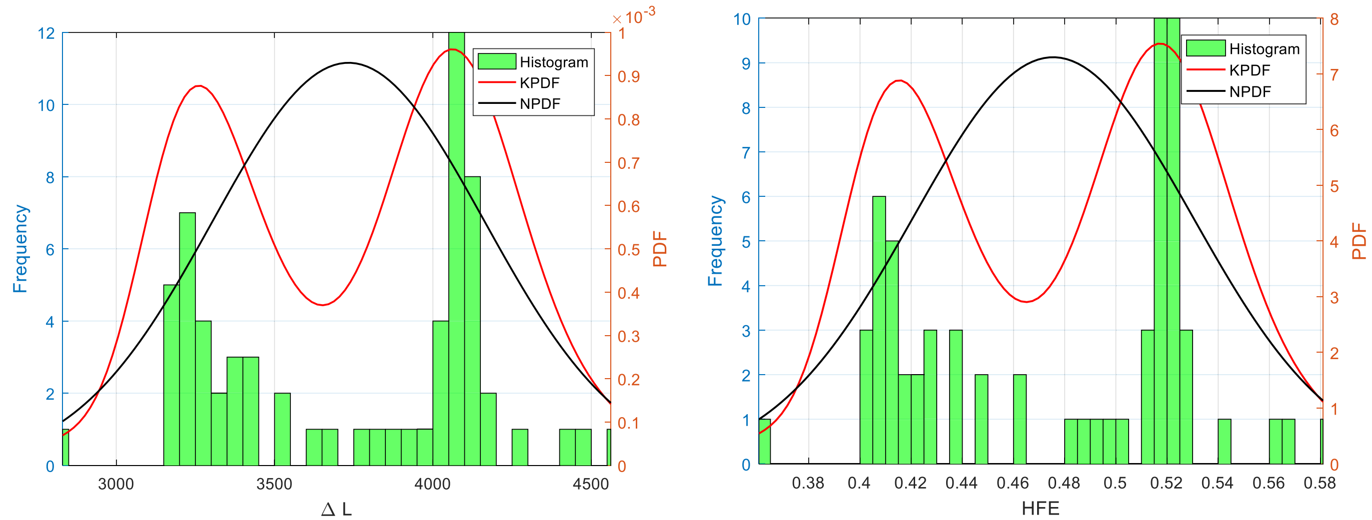

Fig. 16. Additional trajectory length and HFE of the flight FIN 73.

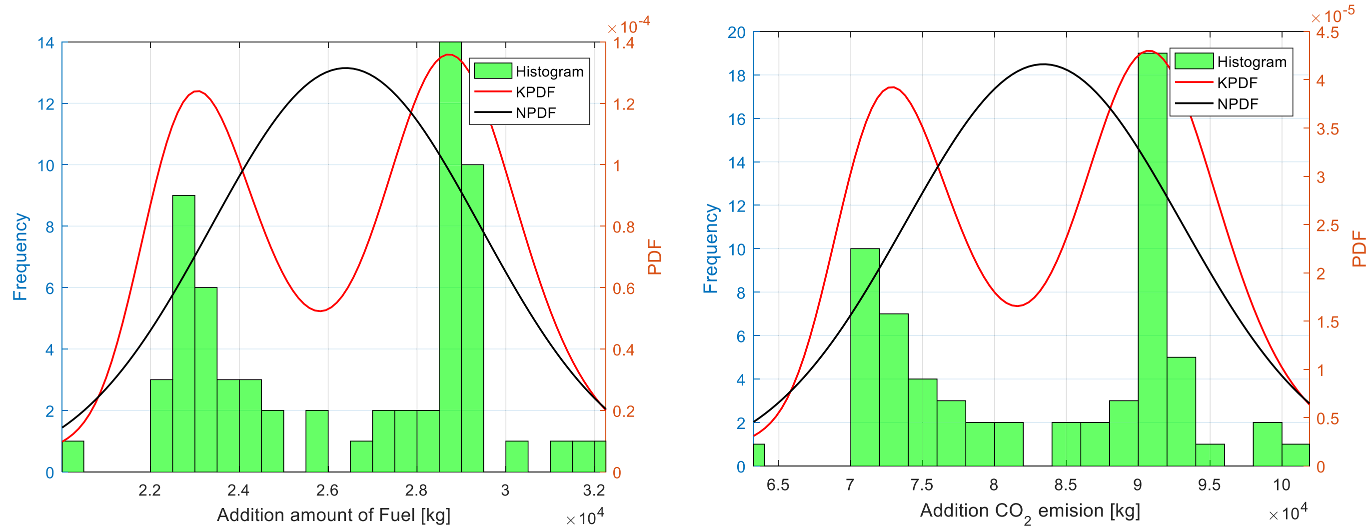

Fig. 17. Additional amount of fuel and CO_2 emissions for the flight FIN 73 due to the overflying of the closed airspace.

for KORD airport.

In a more practical way, the impact of the closed airspace could be estimated for each pair of airports. Excessive additional trajectory length may lead to the closure of direct connections due to their economic inefficiency.

Results of the additional trajectory length estimation for Asian airports are given by countries in Table 2 for EHAM airport and in Table 3 for KORD airport correspondently. Flight connections between EHAM and airports of Japan, South Korea, Mongolia, China, and Kazakhstan were affected the most by a mean value of additional trajectory length. Direct flights from KORD airport to the counties bordering with the closed airspace in central Asia were affected the most (Mongolia and Kazakhstan). Flight connections to India and Thailand are also affected due to its location in the central part of the closed airspace at the longitudinal side.

A graph of flight connections from EHAM and KORD airports with destinations in Asia is shown in Fig. 12. A graph is weighted by the value of additional trajectory length.

Results of airport network analysis help to identify the most affected flight connections globally. We use 362 large airports globally, out of closed airspace, to estimate additional trajectory length. The top 100 of the most affected pairs of airports by additional trajectory length are shown in Fig. 13.

The obtained results indicate that direct flight connections from North America to airports in central Asia (including the following destinations: UACC, ZMCK, ZWWW, UAAA, UAFM, and UAIT) are affected the most. Flight connections from the North European airports EFHK, ENTC, ENVA, and BIKF to West Asia have been affected seriously.

5.2. *Statistical analysis of the air traffic data*

Ukrainian airspace has been closed since Feb 24, 2022. Russian and Belorussian airspaces have been limited to use for many users since 2022, also. The closure of airspace for more than two years has had a serious influence on the global air transportation system. The effect of the closed airspace can be estimated with the help of statistical processing of historical flights data. We use a dataset of historical flights obtained by the open network of software-defined receivers (Flightaware, 2024; OpenSky, 2024). Commercially available databases provide easy access to airplane trajectory data, which are collected from position reports shared by ADS-B technology (Ostroumov and Kuzmenko, 2022).

During the flight planning stage airlines use a cost-efficient trajectory configuration based on the forecasted weather distribution over the

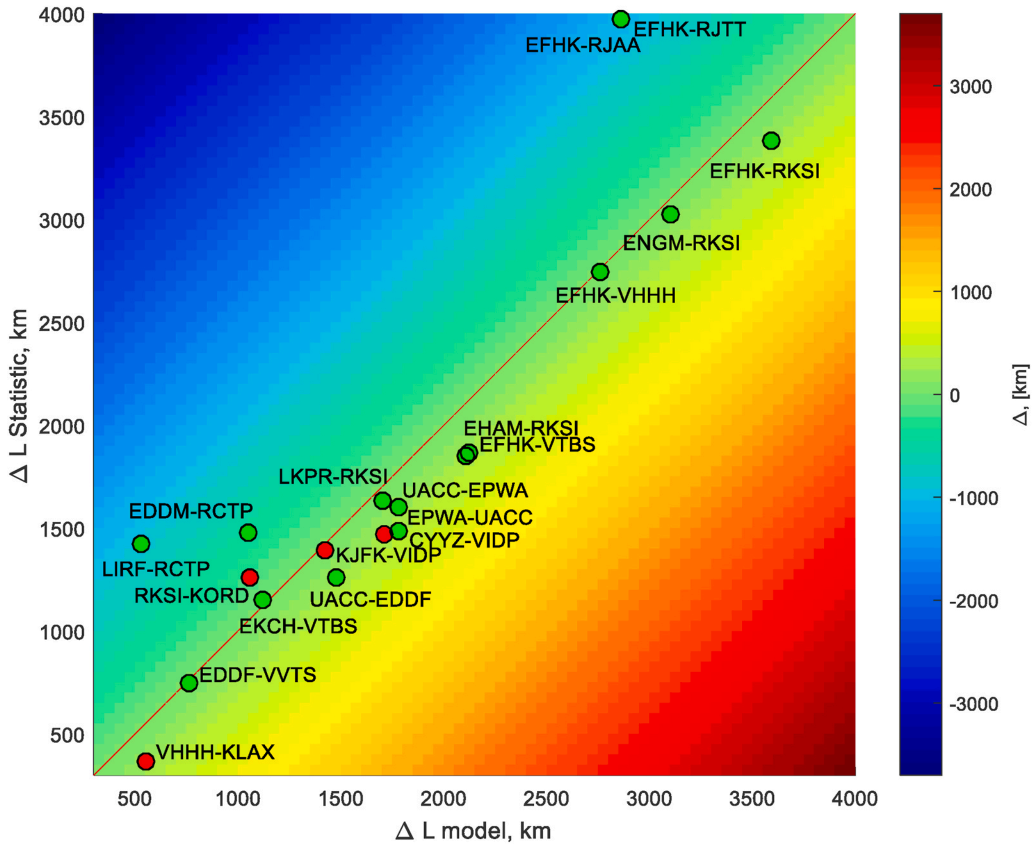

Fig. 18. Comparison of additional trajectory length estimation by statistical air traffic analysis and computer model. Source: own figure generated in the developed software.

flight path. Actual airplane trajectories vary along the shortest path to make maximum impact from local wind distribution. Weather impact makes each airplane trajectory unique. Therefore, airplane trajectory data require statistical data processing to obtain parameters of particular flight connection.

In statistical analysis, we consider flight FIN73 connecting Helsinki-Vantaa International Airport (Finland, EFHK) and Narita International Airport (Japan, RJAA) operated by Finnair. The available data set includes 64 flight trajectories from March 30 to Jun 27, 2024. Also, we used one trajectory of the flight FIN73 in January 2022 to show flight trajectory configuration before the airspace has been closed. Airplane trajectories of the flight FIN73 are shown in Fig. 14.

Results of the statistical analysis of total trajectory length and total flight time are shown in Fig. 15. Results of estimation of additional trajectory length and HFE by (3) are given in Fig. 16. A Normal Probability Density Function (NPDF) and a Kernel Probability Density Function (KPDF) have been fit each parameter.

The geometry of closed airspace for the flight connection EFHK-RJAA is critical. Additional trajectory length in comparison to the shortest path length for the flight FIN73 reached 4561 km (HFE = 0.58). However, mean total flight time is increased for 31 min only (Before: 12 h 27 min; mean total time of the investigated flight for trajectories, which avoid entering the closed airspace is 12 h 58 min). Local weather action in the region caused a decision of sides to overfly the closed airspace. About 39 times wind direction and speed make a positive impact on airplane flight over the Arctic Ocean during March–June 2024. Two sides of possible trajectory planning for avoiding entering the closed airspace give two maximums in histogram of additional trajectory length.

During the considered period the flight FIN73 has been served by Airbus A350-900 aircraft. The average fuel consumption for en-route phase of the flight for A359 is 7.07 kg per km. According to this simple fuel consumption model, an extra amount of fuel can be estimated. Also, extra fuel burn led to the additional carbon dioxide (CO_2) emissions in the atmosphere. During the en-route phase of the flight (with an assumption of no climbing and descending) 1 kg of burned jet fuel generates 3.16 kg of CO_2. Results of calculation of the additional amount of fuel and CO_2 emission for the flight FIN 73 are given in Fig. 17.

The results in Fig. 17 indicate that a one-way overflight of the closed airspace requires an additional 23 tons of fuel mean, resulting in approximately 72 tons of CO_2 emissions. An alternative overflight trajectory configuration requires 28.5 tons of fuel, producing 90 tons of CO_2 emissions. In total, 64 FIN73 flights contribute an additional 5338.4 tons of CO_2 emissions to the atmosphere.

5.3. Verification

Verification of the obtained results could be performed by their comparison with real flights data. Trajectory data fixed by a ground network of ADS-B receivers is used to calculate the trajectory length of particular flight numbers. The 20 most affected unique flight connections, impacted by the closure of the considered airspace, were selected for analysis. One way flight connections are considered only. The following flight numbers are used in the analysis: HVN30 (EDDF-VVTS), FIN41 (EFHK-RKSI), FIN61 (EFHK-RJTT), FIN68 (RJBB-EFHK), FIN73 (EFHK-RJAA), FIN99 (EFHK-VHHH), FIN141(EFHK-VTBS), LOT195 (EPWA-UACC), LOT196 (UACC-EPWA), KAL510(EHAM-RKSI), KAL542 (ENGM-RKSI), KAL970 (LKPR-RKSI), THA951 (EKCH-VTBS), EVA72 (EDDM-RCTP), CAL 76 (LIRF-RCTP), DLH648 (UACC-EDDF), KAL37 (RKSI-KORD), UAL802 (VHHH-KLAX), ACA42 (CYYZ-VIDP), and AAL292 (KJFK-VIDP). Raw trajectory data collected by one flight number are used to calculate the total flight length as the sum of legs estimated by (1). A dataset of historical flights for the last four months

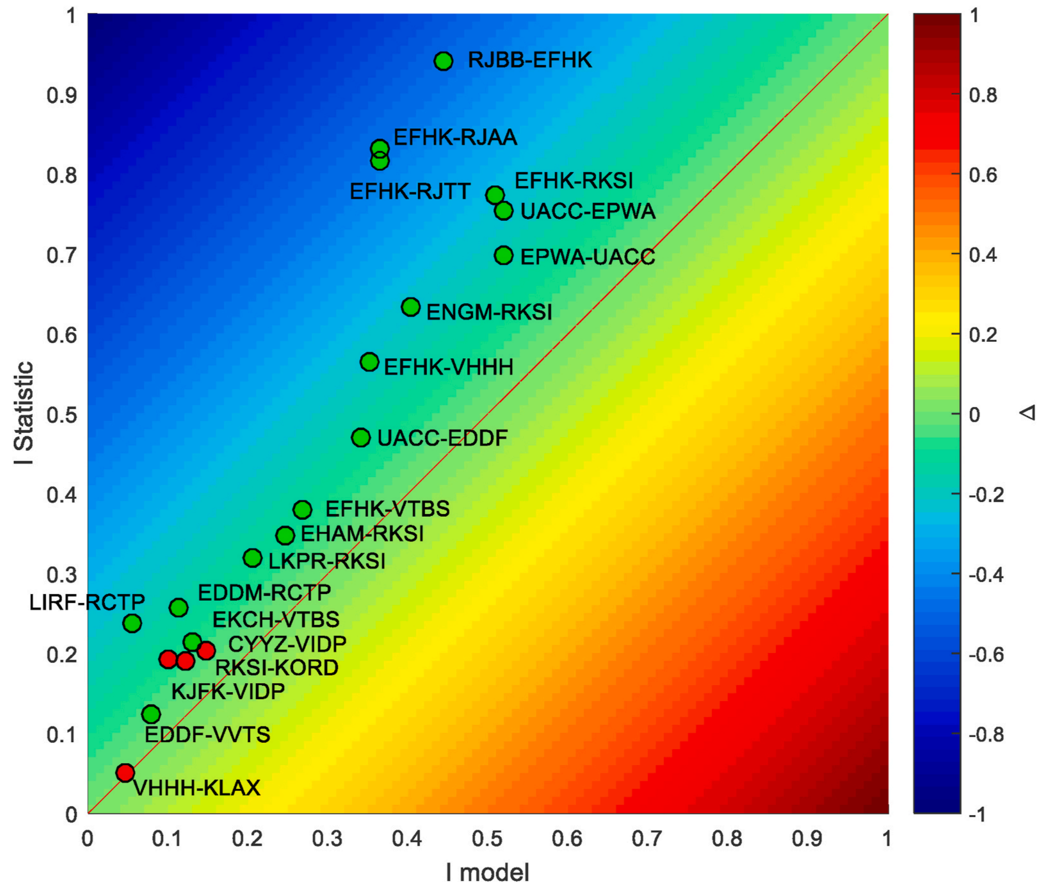

Fig. 19. Comparison of HFE index estimation by statistical analysis and computer model. Source: own figure generated in the developed software.

before May 19, 2024, is used for statistical data processing. Results of statistical analysis of additional trajectory length and HFE values are compared with data obtained by computer simulation of the network and presented in Figs. 18 and 19 correspondently.

The positioning of markers along the diagonal of the diagram in Fig. 18 indicates a strong correlation between the results obtained from statistical analysis and those predicted by the proposed model.The mean error value calculated as a difference between simulated and statistical estimators is below 143 km, and the standard deviation error is 505 km. Only two flights, EFHK-RJTT and EFHK-RJAA, are shifted by over 1000 km due to the avoidance of trajectories over the North Sea. Instead, these flights utilise routes closer to the continental side to benefit from more reliable air navigation services and favourable weather conditions.

Results of HFE index estimation in Fig. 19 give shifted up values. These results prove that aircraft do not use the closest trajectory along the closed airspace boundaries, but also use weather data to get efficient trajectories. Thus, efficient trajectories always vary from the closed airspace based on wind distribution in the region. The HFE index calculated by air traffic statistics is bigger than estimated by computer simulation (see Fig. 19). Also, HFE for flights from North America to Asia (marked by the red marker in Figs. 18 and 19) gives small values due to the long trajectory length.

6. Discussion

The Russian-Ukrainian war caused significant limitations in the available air transportation system. Closed Ukrainian airspace and limited in use airspaces of the Russian Federation and Belarus make a barrier for direct flight connections between North American and Asian airports. Previous studies analyzed the impact of closed airspace based on the statistical data from historical flights. In our research, we use a global air transportation graph to estimate the effect of the closed airspace configuration in any flight connection, even which has not been operated before. The proposed approach can be used to analyze the impact of the closed airspace for any pair of departure and destination airports around the globe. The impact of the configuration of closed airspace on the air transportation network is analyzed with affected areas of a particular level of additional trajectory length and HFE. Area analysis indicates the importance of each airspace based on the level of its impact on the transportation system. Estimated cumulative functions of area analysis are the main scholarly result of the research for the considered closed airspace. Also, the top 100 most affected flight connections due to the restrictions in airspace usage have been identified.

Statistical analysis of air traffic data is used for comparison and verification of the obtained results with trajectory data of real flights. The 20 unique flight connections have been used for verification of the proposed model.

The proposed model is based on the shortest path selection algorithm and does not consider weather distribution along the flight path. Wind direction and speed are used in a cost function of the efficient trajectory planning algorithms used by airlines. In addition, many regions in the world are in the process of FRA integration with all air traffic using a conventional flight routes network. Using a global air transportation graph for those regions leads to addition errors. Thus, the results of statistical analysis in Figs. 18 and 19 caused small variations from the results of computer modelling.

Another significant consideration is that some countries have not implemented sanctions against the Russian Federation and Belarus. It permits airlines registered in these countries to continue usage of Russian and Belarusian airspace. However, the use of these airspaces carries a high risk of exposure to military activities. Furthermore, military forces may close specific flight information regions (FIRs) for an unspecified period of time, diverting air traffic to holding patterns near the boundaries of these regions. Additionally, military activities such as jamming and spoofing of navigation signals can severely impair positioning accuracy, thereby increasing risks to civil aviation. Despite these dangers, many airlines continue to operate in high-risk airspace, creating unfair competition within the aviation market.

7. Conclusions

Normal operation of the global air transportation system depends on airspace status. Closure of some part of airspace for civil aviation users limits air transportation systems in flight routes planning. Closed airspace requires airspace users to replan their trajectories to avoid entering restricted volumes. The efficiency of new trajectories is measured by additional trajectory length and HFE.

War in Ukraine led to the closure of a huge part of airspace that together with limited airspace volumes in the Middle East region caused serious effects on the global air transportation system. Direct flights from Europe and North America to Asian destinations have been affected significantly.

The proposed global air transportation graph could be a useful tool for studying the potential of each segregated part of the air transportation network for direct flight connections. The proposed approach helps to predict the impact of the closure of any part of airspace on the global air transportation system even in case an airspace is still open. The results of such analysis will help to minimize losses before the airspace is closed. Simple graph analysis helps to identify the most affected flight connections over the globe due to the closure of a particular airspace.

Results of the computer simulation of losses in the total trajectory length have been compared with the results of statistical analysis of air traffic for the last four months. The obtained results prove a sufficient reliability level of the proposed model and the possibility of its practical implementation for the analysis of impact on air transportation system caused by the closure of airspace.

In future works, we expect to provide data processing of a complete historical data set of airplane trajectories at the end of the war to get an overall statistical analysis of the war impact on the air transportation system. Also, the proposed approach could be used for the evaluation of the airspace parameters of each country in the world.

CRediT authorship contribution statement

Ivan Ostroumov: Software, Methodology, Conceptualization. **Viktoriia Ivannikova:** Methodology, Investigation. **Nataliia Kuzmenko:** Visualization, Software, Data curation. **Maksym Zaliskyi:** Validation, Investigation, Formal analysis.

Acknowledgments

This project has received funding through the EURIZON project, which is funded by the European Union under grant agreement No.871072 (Project EU #3035 EURIZON "Research and development of Ukrainian ground network of navigational aids for increasing the safety of civil aviation").

Appendix

Table 1
Abbreviations of airport codes

Airport Name	ICAO Airport Codes
Keflavik Airport, Iceland	BIKF
Toronto/Lester B. Pearson International Airport, Canada	CYYZ
Frankfurt Main Airport, Germany	EDDF
Muenchen Airport, Germany	EDDM
Helsinki Vantaa Airport, Finland	EFHK
Amsterdam Schiphol Airport, Netherlands	EHAM
Kobenhavn/Kastrup Airport, Denmark	EKCH
Oslo/Gardermoen Airport, Norway	ENGM
Tromso/Langnes Airport, Norway	ENTC
Trondheim/Vaernes Airport, Norway	ENVA
Lotnisko Chopina W Warszawie Airport, Poland	EPWA
John F Kennedy International Airport, USA	KJFK
Los Angeles International Airport, USA	KLAX
Chicago O'Hare International Airport, USA	KORD
Roma/Fiumicino Airport, Italy	LIRF
Praha/Ruzyne Airport, Czech Republic	LKPR
Taiwan Taoyuan International Airport, Taiwan	RCTP
Narita International Airport, Japan	RJAA
Kansai International Airport, Japan	RJBB
Asahikawa Airport, Japan	RJEC
Tokyo International. Airport, Japan	RJTT
Incheon International Airport, South Korea	RKSI
Almaty Airport, Kazakhstan	UAAA
Nur-Sultan Airport, Kazakhstan	UACC
Manas International Airport, Kyrgyzstan	UAFM
Turkistan Airport, Kazakhstan	UAIT
Hong Kong International Airport, Hong Kong	VHHH
Indira Gandhi International Airport, India	VIDP
Suvarnabhumi International Airport, Thailand	VTBS
Tan Son Nhat International Airport, Vietnam	VVTS
Chinggis Khaan International Airport, Mongolia	ZMCK
Urumqi/Diwopu Airport, China	ZWWW

Source: Airport names are obtained from www.skyvector.com.

Data availability

Data will be made available on request.

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Glossary

ADS-B: Automatic Dependent Surveillance-Broadcast
FRA: Free Route Airspaces
HFE: Horizontal Flight Efficiency
KPDF: Kernel Probability Density Function
NPDF: Normal Probability Density Function